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Realtime Assessment of Nuclear Materials

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***Abstract*– Our group at Livermore Lab specializes in nuclear materials measurements and assessments. We have built detectors that we have taken from breadboard to fieldable. We have even commercialized some detectors for rugged non-expert use, such as the Fission Meter - a thermal neutron multiplicity counter and the Detective - a mechanically-cooled germanium spectrometer. We are currently developing instrumentation and analysis algorithms that rely on fast neutron and gamma scintillator detectors. Our systems merge data from dozens of detectors at rates of a million events per second. Fast neutron and gamma arrival times and energy can be used to assay fissioning materials and estimate moderation and shielding, as well as make 3-D images. The underlying hardware and software to operate these detection systems represent a jump in complexity from the previous systems and are similar to subsystems of high energy and particle physics. We will describe the challenges to convert these scintillator detection systems from expert-user laboratory instruments to non-expert field use, including automating pulse-analysis, data-cuts, data-calibration, data-compression, and especially real-time analysis and assessment.**

I. Introduction

The term "special nuclear materials" (SNM) describes materials capable of neutron-induced fission and fission chains. These materials are closely monitored because SNM is the key to nuclear weapons and nuclear reactors. SNM monitoring capabilities are desirable for counter-terrorism, non-proliferation, and safeguards applications, all of which involve non-expert technicians needing rugged systems that provide high-level interpretations of measurements. SNM includes all fissile isotopes and their chemical forms. The nuclear decay of these isotopes causes them to emit penetrating radiation, primarily in the form of gamma-rays and neutrons. These emitted particles are essential for assessing a sample of SNM so that one can tell its constituent parts, their amounts, their shape, and the chemical form, and the surrounding materials such as shielding. The fundamental information is the arrival times, energy, and type of particles. Good assessment depends on building a high-efficiency system with time and/or energy resolution commensurate with the internal workings of the material.

Over the years, an extended group at Lawrence Livermore National Laboratory (LLNL) developed a few instruments intended to provide non-experts with the capabilities of assessing the composition of radiation-emitting materials, particularly SNM. Non-experts require rugged-use low-maintenance detection systems featuring internally complex analysis tools with simple interfaces that provide answers in realtime. Decaying isotopes that emit gamma-rays with unique spectral signatures can be detected using high resolution gamma ray spectrometers. For non-physicist field use, LLNL carried out the original development of Ortec's Detective [1], a human-carryable germanium-based gamma spectrometer that features mechanical (non-cryogenic) cooling and internal spectral analysis. The on-board spectral analysis packages provide high-level assessments to the user.

Neutrons provide a different kind of signature from that of gamma-rays. Neutrons penetrate high-density materials like metallic SNM more easily than gamma-rays do. The most-accessible signatures made by neutrons lie in the correlated bursts as isotopes decay and emit neutrons, and as the emitted neutrons induce further chains of fission. The rate and sizes of bursts escaping from the materials gives evidence of the kind or kinds of SNM emitting the neutrons. Fission neutrons are emitted at MeV energies, and MeV neutrons are called "fast neutrons". As the neutrons move through material, particularly low-Z material, they slow down until their energies, at small fractions of 1 eV, are comparable to that of gasses at room temperature, at which point they are called "thermal neutrons". Thermal neutrons can be detected using helium-3 in sealed tubes that are rugged and nearly leak-proof. Helium-3 is sensitive to thermal neutrons and not to fast neutrons, so if helium-3 is to be used to detect fast neutrons, the detector must be surrounded by a thermalizing medium, also called a moderator, like plastic. For non-physicist field use, LLNL performed the original development of Ortec's Fission Meter [2] to collect either thermal neutrons or neutrons thermalized in accompanying plastic panels. Like the Detective, the Fission Meter is human-carryable and includes analysis tools that assess properties of SNM.

II. Gamma and Fast Neutron Detection System

As noted above, helium-3 detection requires thermalizing the fast neutrons that are emitted by SNM. Thermalization takes tens of microseconds, and obscures information on the timescale of fission and fission chains, which are in the range of 10 nanoseconds to 1 microsecond. In the past seven years, this group began measuring SNM using arrays of liquid scintillator detectors that are sensitive to both gamma-rays and fast neutrons, and have a time resolution of about one nanosecond. The signatures of the rates and sizes of the fission bursts at this timescale do a better job of separating different processes occurring in the SNM assembly. The systems we use to assess fast neutrons from SNM assemblies are more complex than the Detective and the Fission Meter, and so

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provide the latest challenge to building a portable SNM assessment tool for non-experts.

The gamma and fast neutron detectors are liquid scintillators in sealed 3-inch-thick by 4-inch-diameter containers, each one separately read out using a photo-multiplier tube. Our detector modules are made by Eljen and use either EJ-301 or EJ-309 scintillator, coupled to Photonis or Hamamatsu PMTs. These scintillator materials are sensitive both to gamma rays and fast neutrons, and have the property that pulses of light created by a neutron causing a proton to recoil have broader pulse-tails than those created by a gamma-ray interacting with an electron [3]. This property leads to the ability to discriminate particle types by pulse shape using pulse shape discrimination (PSD) if the pulse-detecting electronics have properties sufficient for determining shape [4]. Because we are measuring correlated particles, we require high geometric efficiency and obtain it by surrounding the measured item with scintillator modules, as in a helium-3 well-counter. For example, a spherical region roughly one-half meter in diameter can be surrounded by 50-100 modules with 4-inch diameter faces. This adds the requirement that we must be able to read out 100 modules. The pulses from the PMTs travel down cables that are typically 10-meters and into separate channels on high-speed VME digitizer boards built by Struck Innovative Systems (SIS). Over the years, we have used a few different SIS digitizers with different numbers of channels per board, different sampling rates, and sample resolution (bits per sample). It is generally agreed [5] that 12-bits per sample and 250 Msamples/sec are acceptable for digitizing pulses from liquid scintillators in order to obtain arrival time at 1 nsec resolution, deposited energy at 20% resolution, and particle type from PSD. Most of our development arrays use SIS3320 8-channel 200 MS/s 12-bit boards reading out 72 modules with one extra board that is a common clock (SIS36/38XX) and another USB-VME interface board (SIS3150). A big advantage of the architecture of the SIS digitizers over other digitizers we evaluated is that all the channels can process pulses simultaneously, leading to no interchannel deadtime, and the per-channel retrigger time is less than a microsecond. Our newest system is 72 modules and uses SIS3316 16-channel 250 MS/s 14-bit VME boards that share an internally generated clock and are separately controlled and read-out over gigabit Ethernet.

Each event must be "calibrated", meaning that the system-dependent information (clock time, module number, and pulse shape information) must be converted to system-independent information (experiment time, energy, and particle type), using either a system response model or a summary of a pre-runtime training data-set or, ideally, both. The events in each channel are stored in separate on-board buffers. Because the arrival times are essential to the analysis, a time-sort is unavoidable. Before sorting, the timetags on all events in each channel must be offset by that channel's offset from the whole system. Module-to-module time-correction, also called differential latency, is a per-channel time correction derived from pre-runtime training data and stored in a lookup table. Jitter is handled at runtime by computing a subsample offset – based on the concept of constant fraction discrimination – on the digitized samples of the pulse. After the two offsets are applied, the events from all modules can be sorted together.

In addition to time correction and time-sorting, the current system requires several steps to do the rest of conversions. The first step uses pre-runtime training data from a gamma line-emitting source, like cesium-137, to convert the size of each module's pulses to a corresponding gamma equivalent energy from fitted spectra. The liquid scintillator lacks a photo peak, and so a fit is done to the spectrum's Compton edge to obtain the conversion. The energy conversion fit parameters for each module are stored in an array and applied to each module's pulses. The second step, to obtain particle type, uses a different set of pre-runtime training data that contains gammas and neutrons, typically a californium-252 source shielded by more than an inch of lead. The basic idea is to obtain properties of the distributions of gammas and neutrons in sampled-pulse feature space and apply them to each pulse from the measurement to determine the type of particle that made the pulse. There are many techniques to do this, as in [6]. In the time since readouts have evolved from analog to digital, PSD strategies have also evolved from merely mimicking analog techniques, to doing simple math, to implementing esoteric signal processing and machine learning techniques. Because high data-rates prevented us from transferring all the samples from each pulse, we were forced to compress the raw data to only 8 accumulated sums of consecutive samples, notably the total pulse and late "tail" pulse with the head-to-tail cutover optimized as described in [7]. Using these sums we compute a "particle score" from the tail-to-total ratio. For a series of energy bins, we fit Gaussians to the neutron and gamma ensembles in the training data and then choose the particle-type threshold using these Gaussians. The apparent simplicity has a cost in precision and reduction time because the interpretation of the model depends on binning the energy, doing several logic tests and sums, differences, products, and divisions. Finally, after the pulses are associated with a particle type, the energies for events identifies as neutrons are corrected by the "quench", which is the conversion between gamma equivalent energy and neutron deposited energy. We determine the quench using pre-runtime training data that includes a set of time-of-flight measurements whose results are summarized in a lookup table.

After the calibration, the data are cut various ways to build distributions that may be analyzed by the theory code. The most common cuts remove events whose particle type is ambiguous (falling somewhere between the training set clumps for gammas and neutrons), whose pulse has been flagged as "pileup" by the digitizers using a second trigger, and also, for the neutron-only analysis, only using the fast neutrons as the correlated particles.

All the separate processing and cuts based on pre-runtime training data and lookup tables can be time-consuming. There are several possible approaches to increasing the speed, including combining the logic and math steps from separate calibrations into one, and performing the simpler math and cuts on the digitizer boards.

The next phase of computation requires summarizing the data for analysis, as in [8]. The summaries perform two roles: the first is to convert the ensemble of events into a multi-dimensional distribution of rates and sizes of bursts. The second is to provide a compact data format for transmission. If the events are arriving at hundreds of thousands per second for a few minutes, and consist, even in their reduced form, of 10 bytes of data per event, the reduced data set is of order one gigabyte. A judicious summary of events, in a projection or histogram, is of order a megabyte. The megabyte size provides a more useful form for rapidly transferring data collected by a non-expert at a remote location to an expert user for further analysis.

III. Strategies for Faster Processing

During the long development phase, system integration was more important than fast assessment. Now as we have started to emphasize improvements to realtime processing, we are starting to match hardware performance to the expected rates of data taking and data reduction.

We have a medium-term goal of handling one-gigabit of raw data in near-realtime. This target rate is set both by the SIS3316 digitizer cards' gigabit Ethernet rate feeding a single hub connected to the host computer, and also by a simple estimate of 100 samples per pulse, 10,000 pulses per second per module, and 100 modules. The number of samples per pulse is set by the sampling rate and length of a pulse from pre-trigger to end of pulse, approximately 100 samples of a one-half microsecond pulse and pre-trigger at 200 MSamples/sec. The rate of pulses per module is set by the length of a pulse from pre-trigger to recovery to re-trigger, about a microsecond. If the random rate keeps the rate of piled-up following pulses below 1% (so that about 99% of all triggering pulses are not contaminated by other triggering pulses), then the rate must remain below about 10,000 pulses per second per module. The estimate, then, is 10^8 samples per second for the entire system, which for 2-byte samples, is 1.6 gigabit per second streaming into the digitizers.

Once the full waveforms have been streamed onto the computer's disk at a gigabit per second, it is necessary to develop software capable of calibrating, reducing, and analyzing the data at the same rate. We are examining several strategies. Under high pulse-rate conditions, it is probable that we would like to remove useless pileup pulses long before before transferring to the host. This is comparable to a veto, but under conditions that depend on the property of the pulse in question. Some digitizer vendors are starting to provide on-board PSD with an option for on-board rejection of non-neutron events [9]. At the other end of the process, we are beginning to examine folding the multi-step calibration process into one support vector machine computation, as in [10]. This computation can be implemented easily on a GPU which should be able to keep up at the required gigabit datarate.

IV. Conclusion

The Liquid Scintillator Array represents a jump in complexity from earlier detection systems we have developed and that have been commercialized. Some aspects of the system have been implemented to operate in realtime, others have yet to be realized.

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